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Rice Drying Rates

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RICE DRYING RATES

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PREFACE

The following report is a copy of a thesis prepared by Jairo F. Robayo as part of his studies for a Master of Science Degree. The purpose of this research was to determine the factors which affect rice drying rates.

The basic approach used was to divide the drying process into separate processes, including temperature equilibrium between the grain and air, moisture removal and evaporative cooling of the air and grain. Prediction of the amount of drying that occurs in a thin layer of rice can be made by considering the initial air and grain conditions using a thin layer drying equation and complete heat balances to predict the final air and grain temperature.

Mr. Robayo was sponsored by the Bank for International Development and was given leave from IDEMA, S.A. of Colombia for his studies. His research was supervised by Dr. Harry Pfost, Professor, Department of Grain Science and Industry assigned to the AID/csd-1588 Technical Assistance Contract in Food Grain Drying, Storage and Transportation.

The results in the different tests indicated that the drying rate was faster at the beginning of the drying operation and one of the most important factors was the air drying temperature.

INTRODUCTION

Rice ordinarily is harvested at moisture contents above safe storage levels, so additional drying usually is needed. The grain is harvested together with its husk or hull and is called rough rice or paddy.

A great many studies have been made to develop formulas for computing grain drying rates, but none has been universally accepted.

This research was conducted first of all to develop an empirical equation for drying a thin layer of rice and then to develop a mathematical model that incorporates many of the factors that affect grain drying, and would thus be capable of determining the effects of many drying parameters on the drying results.

The equation that we used for thin layer drying is an empirical equation that was developed by T. L. Thompson on his mathematical model of corn drying. We followed the same pattern that he used, but it was necessary to change all parameters and to fit new ones for rice.

The drying process was considered to be divided into separate processes, including temperature equilibrium between the grain and air, moisture removal, and evaporative cooling of the air and the grain.

In order to obtain the different parameters, four drying tests were made with temperatures from 100°F. to 130°F.

With this mathematical model it was possible to find the rate of drying rice.

REVIEW OF LITERATURE

Excess moisture in grain is the biggest problem encountered in storing it safely. Grain can be harvested satisfactorily with a combine as soon as it is ripe (15), but it contains too much moisture for safe storage. A practical method of drying, therefore, gives two principal advantages: First, it permits harvesting the grain as soon as it is ripe and mature and thus avoiding field losses. Second, it places the grain in a condition for safe storage as dry grain, thereby avoiding storage losses from molds and, to an appreciable extent, from insects. Drying is the universal method of conditioning wet grain to preserve its quality and nutritive value for feed and food, and its germination for seed.

In all practical grain drying systems, air is used as a medium for removing moisture from the grain as it is evaporated. Evaporation of the moisture from the grain requires energy in the form of heat. This heat is normally supplied by the air forced through the grain--either its natural contained heat or added supplemental heat.

The amount of moisture which air can pick up and transport as it moves through a column of grain is dependent upon its temperature, relative humidity, velocity, distance traveled and the condition of the grain through which it passes. As the air progresses through a column of grain, it picks up moisture and thereby loses some or all of its drying capacity.

Rice Drying Terminology (17)

The United States' rice industry uses a number of specialized terms and measuring units. Some of those associated with drying are discussed and their specific use in the context of this report explained.

Kinds of rice:

Rough rice is the harvested product with hulls intact. In some foreign countries it is called paddy.

Brown rice is the unmilled product, but with hulls removed.

Milled rice is the product from which the outer bran layer and a part of the germ have been removed.

Head rice are whole kernels of milled rice.

Weights:

Rough rice weights are expressed in bags or cwt (100 pounds, 45.36 kgs), bushels (bu, 45 lbs, 20.43 kgs), barrels (bbls, 162 lbs, 73.46 kgs) and metric tons (2200 lbs, 1000 kgs).

Air vapor mixtures (8):

Normal atmospheric air is a mixture of drying air and water vapor, atmospheric air never being completely dry.

Absolute humidity:

The pounds of moisture per pound of dry air is called the absolute humidity. The base (1 lb of dry air) is used since it is a constant for any change of conditions.

$$P_a = P_{at} - P_v$$

where P_a = Pressure exerted by the dry air, lb per sq in.

P_{at} = pressure exerted by the atmosphere, lb per sq in.

P_v = pressure exerted by the water vapor in the atmosphere, lb per sq in.

This being the pressure exerted by the air (dry). P_{at} for standard atmospheric pressure is 14.7 lb per sq in; M is 28.97; M_1 is 18.02.

M = molecular weight of air.

M_1 = molecular weight of water.

Therefore

$$H = \frac{P_v}{P_{at} - P_v} \cdot \frac{18.02}{28.97} = \frac{P_v}{1.605\ (P_{at} - P_v)}$$

H = absolute humidity.

Relative humidity:

It is defined as the ratio of the actual pressure of the water vapor in the air to the pressure if the air were saturated with moisture at the same temperature.

Total heat, enthalpy:

The total heat or enthalpy of an air-water-vapor mixture is expressed by

$$ha = .24t + H\ hg$$

where ha = heat content of the mixture, BTU per lb of dry air, referred to zero degrees for air, and to water at 32°F.

$0.24t$ = average specific heat of dry air.

H = humidity.

hg = heat content of a pound of water vapor at temperature t. This can be taken directly from a steam table or can be calculated from

$$hg = 1075.2 + 0.45\ (t - 32)$$

$$hg = 1060.8 + 0.45\ t$$

and

$$ha = 0.24\ t + H\ (1060.8 + 0.45\ t)$$

The constant 1075.2 is the heat content of a pound of water vapor at 32°F; 0.45 is the specific heat of water vapor.

Adiabatic process:

An adiabatic process is a procedure whereby there is a change from one state to another without heat exchange between system and surrounding. Consider a perfectly insulated system with a change of state from 1 to 2 the heat balance is

$$0.24\ t_1 + H_1\ (1060.8 + 0.45\ t_1) + (H_2 - H_1)\ (t_3 - 32)$$
$$= 0.24\ t_2 + H_2\ (1060.8 + 0.45\ t_2)$$

The water can enter the system at a temperature t_3 which can be above, below, or equal to either t_1 or t_2.

Drying:

Drying systems in which heat energy is supplied only by air, with sensible heat of the dry matter small in proportion to the latent heat of evaporation and with negligible wall exchange, can be treated as cases of adiabatic humidification. As air passes over the material being dried, its temperature drops and its humidity rises, so that the wet bulb temperature remains constant (8).

Moisture content (11):

Moisture content is commonly expressed on the wet basis, the percentage of water present in the wet grain.

$$M_{wb} = \frac{100\ W_w}{W_d + W_w}$$

where M_{wb} = moisture content, wet basis percent.

W_w = weight of water.

W_d = weight of dry material.

It is less common, but equally correct to express moisture content as a percentage of the dry weight of a material. This expression is preferable for analytical purposes because the weight of dry matter remains constant, but the combined weight of dry matter and moisture continually change as drying proceeds.

Moisture content dry basis

$$M_{db} = \frac{100\ W_w}{W_d}$$

Conversion equations for these two expressions are:

$$M_{wb} = \frac{100\ M_{db}}{100 + M_{db}}$$

$$M_{db} = \frac{100\ M_{wb}}{100 - M_{wb}}$$

Equilibrium moisture content:

The concept of equilibrium moisture content is important because it is directly related to the drying and storing of farm crops (3). The equilibrium moisture content is useful to determine whether a product will gain or lose moisture under a given set of temperature and relative humidity conditions. A product is in equilibrium with its environment when the rate of moisture loss from the product to the surrounding atmosphere is equal to the rate of moisture gain of the product from the surrounding atmosphere. The atmospheric conditions are defined by temperature and relative humidity. The moisture content of the product when it is in equilibrium with the surrounding atmosphere is called the equilibrium moisture content or hygroscopic equilibrium.

The relationship between the moisture content of a particular material and its equilibrium relative humidity at the particular temperature can be expressed by means of equilibrium moisture curves. These curves are sometimes referred to as isotherms because the values plotted for each curve usually correspond to a specific temperature.

An empirical equation is used to represent the equilibrium moisture content (6).

$$1 - RH = \exp(-CTM_e^n)$$

in which RH, the relative humidity, is represented as a decimal; T, the absolute temperature, deg R; M_e the equilibrium moisture content, percent, d.b.; and C and n are constants varying with the materials.

Like other grains, rice is hygroscopic and will gain or lose moisture until it is in equilibrium with the air it contacts. The equilibrium moisture content (2) primarily is dependent on the relative humidity, but it varies to a lesser degree with air temperature. Rice losing moisture due to exposure to air at any given temperature and relative humidity has a slightly higher equilibrium moisture content than does rice adsorbing moisture due to exposure to the same air.

Karon and Adams (11) give equilibrium moisture contents for rough rice with air at 77°F and relative humidities between 11 and 92%. Hogan and Karon (9) give them for temperatures of 80°F, 94°F and 111°F for relative humidities between 48 and 93%.

Heat of vaporization:

The heat of vaporization (1) for water in grain is higher than that for free water of the same temperature. The difference may be assumed to be equal to the heat of wetting, but experimental data of wetting are also scarce. The latent heat is greater at low moisture content and is very nearly the same as for free water at high moisture content.

Othmer (13, 14) developed a basic relationship between vapor pressures of pure liquid and those of solutions and absorbents and he found that a straight line is obtained by plotting on log paper vapor pressure of the liquid under investigation (moisture in the grain in this case) against vapor pressure of a reference liquid (water) at the same temperature.

He developed the following equation:

$$\ln P = \frac{L}{L'} \ln P_o + C$$

in which P = vapor pressure of moisture in the grain that has reached a constant weight when exposed to a given psychrometric conditions. (At this condition the vapor pressure of the moisture in the air and the moisture in the grain are equal.)

P_o = vapor pressure of water.
L = heat of vaporization of moisture from grain.
L' = heat of vaporization of water.
C = a constant.

P, P_o, L and L' one to take at the same temperature

$\frac{L}{L'}$ is the slope of a constant grain moisture content line in the Othmer graph.

Chung and Pfost give a formula for calculating the isoteric heat of sorption (2)

$$\Delta H_d = R \left(\frac{T_1 T_2}{T_2 - T_1}\right) \ln \frac{P_2}{P_1}$$

ΔH_d = isoteric heat of desorption $\frac{BTU}{lb\text{-}mol}$

P_1 and P_2 are equilibrium vapor pressures at temperatures of T_1 and T_2 respectively, which are the absolute temperatures.

R = Universal gas constant 1.98 $\frac{BTU}{(lb\text{-}mol)°R}$

However to get a better approximation, take the value of $\Delta H_{s\varepsilon}$ as applying to an average isotherm whose temperature T is given by

$$\frac{1}{T} = \frac{1}{2}\left[\frac{1}{T_1} + \frac{1}{T_2}\right] \text{ and}$$

whose pressure is given by $P = \sqrt{P_1 P_2}$

Specific heat:

G. H. Haswell (4) found that the specific heat of rough rice was well fitted by a straight line, he used for his experiments a modified Bunsen Ice Colorimeter and from his tests on rough rice, he determined the following equation

$$C = 0.0107\ M + 0.265$$

M = moisture content % wet basis.

Rate periods of drying (3):

There are two major periods of drying (A) the constant rate periods and (B) the falling rate period. In the constant rate period drying takes place from the surface of the grain and is similar to evaporation of moisture from a free water surface. The magnitude of the rate of drying during this period is dependent upon (a) the area exposed, (b) the difference in humidity between the air stream and the wet surface, (c) coefficient of mass transfer and

(d) velocity of the drying air. The constant drying period is short in duration for farm crops.

The falling rate period is entered after the constant rate period. The critical moisture content occurs between the constant rate and falling rate periods. The critical moisture content is the minimum moisture content of the grain that will sustain a rate of flow of free water to the surface of the grain equal to the maximum rate of removal of water vapor from the grain under the drying conditions.

In grain the initial moisture content is usually less than the critical moisture content, so that all of drying occurs in the falling rate periods and the constant rate period is often neglected by researchers because of its short duration and the small amount of moisture to be removed before entering the falling rate period. The falling rate of drying is controlled largely by the product and involves the (a) movement of moisture within the material to the surface by liquid diffusion and (b) removal of moisture from the surface.

Thin layer drying:

Thin layer drying refers (3) to the drying of grain which is entirely exposed to the air moving through the product. The equation representing movement of moisture during the falling rate period of drying is based on Newton's equation refers to the heating or cooling of solids and is stated as follows: The rate of change in temperature of a body surrounded by a medium at constant temperature is proportional to the difference in temperature between the body and the surrounding medium when the temperature difference is small.

$$\frac{dt}{d\theta} = -k\ (t - t_e)$$

Experimental (8) drying studies of agricultural products have shown that the drying rate is proportional to the difference in moisture content between the material being dried and the equilibrium moisture content at the drying air state.

$$\frac{dM}{dt} = -(M - M_e)$$

Solution of this equation yields the exponential drying equation

$$MR = \exp\ (-Kt)$$

where $$MR = \frac{M - M_e}{M_o - M_e}$$

M = moisture contents, dry basis at any time in hours t,

M_e is the equilibrium moisture content

M_o is the original moisture content

K is the drying constant

Most investigators state that the drying constant K is dependent on the drying air temperature. It has been shown by Henderson and Pabis (5) that K varies with the air temperature and they give the following expression.

$$K = b\ \exp\ (\frac{d}{t + 460})$$

where b and d are constants.

Grain drying:

Hustrulid and Flikke (10) working with maize and assuming that the kernel represents a sphere of homogeneous material from the mathematics of diffusion that

$$\frac{M - M_e}{M_o - M_e} = \frac{6}{\pi^2} \sum_{N=1}^{\infty} \frac{1}{N^2} \exp\ (-N^2 K\theta) = \frac{6}{\pi^2} C$$

where C represents a series which for large values of $K\theta$ converges rapidly so that this equation is identical to the following equation.

$$\frac{M - M_e}{M_o - M_e} = a \exp\ (-Kt)$$

that was used by Henderson and Henderson (7) in their work of developing a computational procedure for deep bed drying of agricultural grain.

where M_o = initial moisture content

C = a constant

t = time

and K = a exp (-B) (t + 460)

Faulkner and Wratten (18) working with rice, under varying conditions of air velocity, drying air temperatures, bed depth, time and other variables, they developed a prediction equation for moisture removal from rice under varying drying conditions.

$$M_R = 0.042 \left(\frac{t_d}{t_w}\right)^{-0.281} \left(\frac{VT}{X}\right)^{0.5788} \left(\frac{t_d - t_w}{t_1}\right)^{1.004}$$

M_R = moisture removal in time % dry basis

M_i = initial moisture content % dry basis

t_d = dry bulb temperature of drying air

t_w = wet bulb temperature of drying air

X = distance within grain from entering air

T = time from start of drying

t_i = initial grain temperature

V = air velocity

Thompson (16) working with corn gives the following equation for fully exposed, thin layer drying

$$t = A \ln (MR) + B [\ln (MR)]^2$$

where A and B are constants that depends on the air temperature

t = time

$MR = \text{moisture ratio} = \frac{M - M_e}{M_o - M_e}$

He assumed that corn equilibrium moisture content for a given air state point is represented by

$$1 - RH = \exp (-C (T + 50) M_e^n$$

where $C = 3.82 \times 10^{-5}$

$n = 2$

RH = relative humidity.

The latent heat of water was assumed to be represented by the equation

$$L = L' (1 + ae^{-bM})$$

where $L' = 1094 - 0.57\ T$ that is the latent heat of water.

The specific heat of corn was assumed to be represented by the equation

$$C = 0.350 + 0.00851\ M_w$$

He divided the drying process into separate processes including temperature equilibrium between the grain and air, moisture removal, and evaporative cooling of the air and grain and prediction of the amount of drying that occurs in a thin layer of corn can be made by considering the initial air and grain conditions using a thin layer drying equation and complete heat balances to predict the final air and grain temperature.

EXPERIMENTAL PROCEDURE

MATHEMATICAL MODEL

In this research the mathematical model developed by Thompson was used but it was necessary to change all parameters and to fit new ones for rice.

Factors which may affect drying rates are (17):

1. Air temperature and relative humidity (or any other physical or thermal properties of moist grain).
2. Air flow rate.
3. Rice moisture content.
4. Rice temperatures.
5. Moisture distribution within a rice kernel.
6. Rice grain type and variety characteristics.
7. Bed depth of rice in dryer.
8. Resident time of rice in dryer.

The mathematical drying model incorporates many of the factors that affect grain drying and in the following sections is developed this mathematical drying model.

EQUIPMENT

Aeroglide Steam Heated Cabinet Driers

Series No. 25498-1

Model Si-30-10 RSX

The Aeroglide Cabinet Drier is designed for small drying applications and especially test projects. The unit is capable of drying one or more trays of product with controlled air flow (cfm), temperature, makeup air, humidity, and direction of air flow through the product.

Thin Layer Drying

The drying of a thin layer of rice was simulated by considering the changes that occur in the grain and the drying air as shown in Fig. 1.

Drying air with initial temperature T_o °F and absolute humidity H_o lbs of water per lb of dry air is passed through a thin layer of rice with an initial moisture content M_o % d.b. and a temperature G_o deg F. for a drying interval Δt. During this interval ΔM % of moisture is evaporated from the rice into the air increasing its absolute humidity to $H_o + \Delta H$ pounds of water per pound of dry air. During drying the temperature of the drying air is decreased in ΔT deg F in proportion to the temperature increase of the rice ΔG °F and the evaporative cooling accompanying the moisture evaporation. The amount of drying performed was calculated by a thin layer drying equation with constant dependent on the drying air temperature.

Complete heat balances were used to calculate the final air and grain temperature consistent with the evaporative cooling accompanying the moisture evaporation and with the initial temperature of the drying air and the grain.

I presented a detailed analysis of those calculations and the following assumptions or relationships were used in the development of this mathematical model.

a) Fully exposed, thin layer drying is represented by the Thompson equation.

$$t = A\ln(MR) + B[\ln(MR)]^2$$

where A and B are constants to be found.

$$MR = \text{moisture ratio } \frac{M - M_e}{M_o - M_e}$$

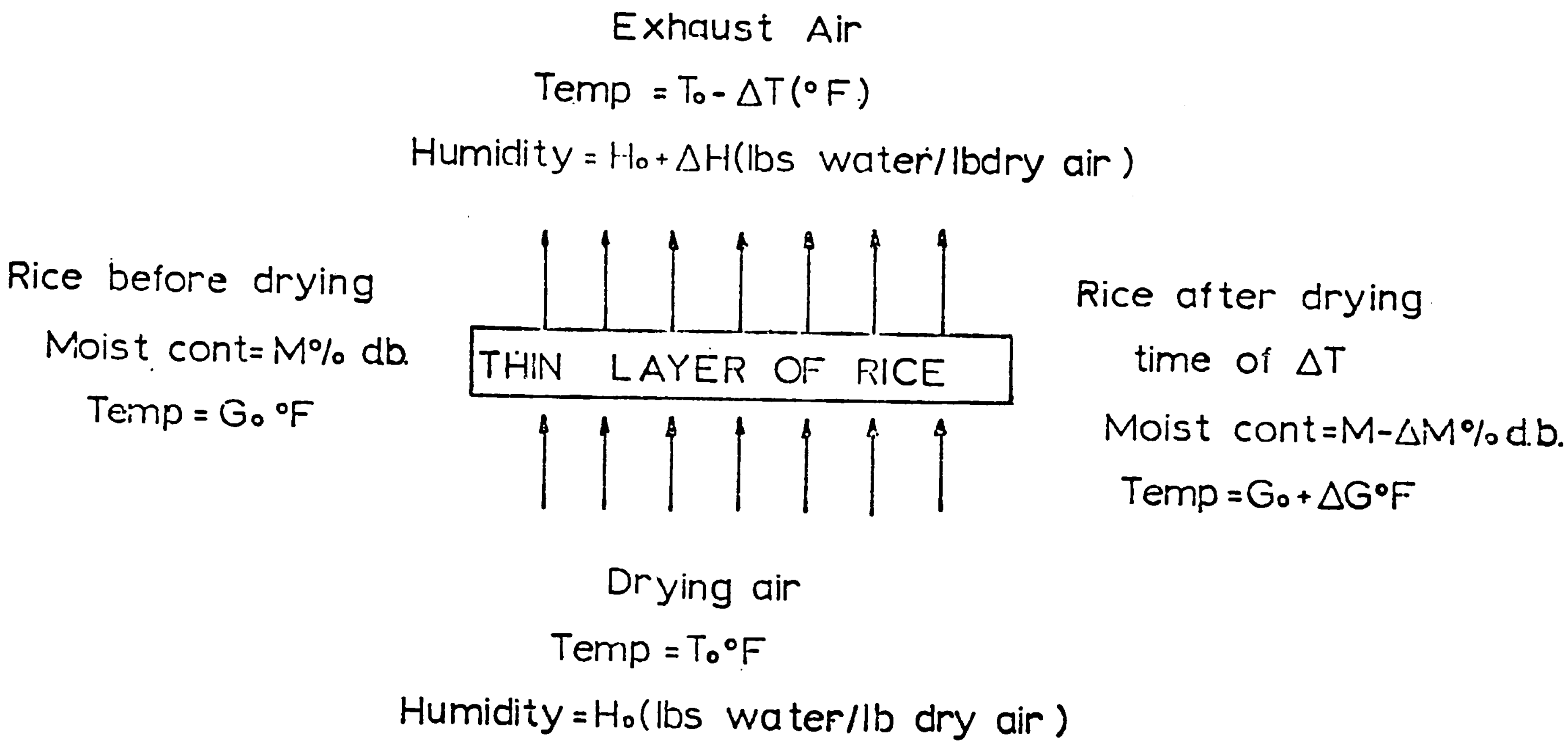

Exhaust Air
Temp = $T_0 - \Delta T$ (°F)
Humidity = $H_0 + \Delta H$ (lbs water/lbdry air)
Rice before drying
Moist cont = M% db.
Temp = G_0 °F
THIN LAYER OF RICE
Rice after drying
time of ΔT
Moist cont = $M - \Delta M$ % d.b.
Temp = $G_0 + \Delta G$ °F
Drying air
Temp = T_0 °F
Humidity = H_0 (lbs water/lb dry air)

FIG. - 1

M = moisture content at time t, percent dry basis

M_o = initial moisture content, percent dry basis

M_e = equilibrium moisture content, percent dry basis

A series of thin layer drying tests were made with different drying conditions. The moisture in the rice was measured taking small samples--30 gr--every 15 minutes and moisture was obtained by the two stage air oven method. Each drying test was terminated when the moisture was reduced to 12.5% w.b. Tests were performed with 28% w.b. initial moisture and 20 cfm/ft^2 of drying air and with temperatures ranging from 100°F to 130°F. In each test, the air temperature, air flow rate and grain depth were kept constant (neglecting the shrinkage effect).

The results from each drying test were plotted in a graph of moisture vs time (Fig. 2).

The first term studied in the former equation was the moisture ratio MR.

$$MR = \frac{M - M_e}{M_o - M_e}$$

M, and M_o were obtained by measuring the moisture content by the air oven method, but for obtaining M_e it was necessary to use an empirical equation. The Henderson equation.

$$M_e = \left[\frac{-\ln (1 - RH)}{C\ (T + 460)}\right]^{1/n}$$

where:

n and C are two constants that depend on the material (6). It was necessary to obtain these two constants for rice.

The following method was used to obtain these values. Wratten and Kendrick (18) developed a table for hygroscopic equilibrium of rough rice, but accuracy of extrapolated data beyond the range of 77°F and 110°F has not verified experimentally. This table was used for the values ranging from 85°F to 110°F and for moisture content between 6% and 17% w.b. and these values were then fitted to the equation of Henderson following this procedure.

$$1 - RH = \exp\ (-C\ (T + 460)\ M_e^{\ n}$$

$$\frac{1}{1 - RH} = \exp\ (C\ (T + 460)\ M_e^{\ n}$$

$$\ln[\ln(\frac{1}{1 - RH})\} = n \ln M_e + \ln C + \ln\ (T + 460)$$

Defining from the above equation

$$y = \ln[\ln(\frac{1}{1 - RH})]$$

$$X = \ln M_e$$

$$\bar{C} = \ln C + \ln\ (T + 460)$$

We obtain a linear equation in n and $\bar{C}$

$$y = nx + \bar{C}$$

using the least squares method on this linear equation the values of n and $\bar{C}$ were obtained for each temperature.

The variation of n vs temperature was very small and therefore an average value of n was assumed.

where $n = 1.91$

In order to obtain C; from the equation

$\bar{C} = \ln C + \ln\ (T + 460)$, the following transformations were made

$$\exp\ (\bar{C}) = C\ (T + 460)$$

$$\frac{\exp\ (\bar{C})}{C} = T + 460$$

applying the least squares method to this equation the value of C was obtained.

$$C = 1.39 \times 10^{-5}$$

Finally the equation for moisture equilibrium M_e is:

$$M_e = \left[\frac{-\ln(1 - RH)}{1.39 \times 10^{-5}\ (T + 460)}\right]^{\frac{1}{1.91}}$$

Making a comparison between the values obtained by Hogan and Karon and the values obtained for this equation (Fig. 3), we can see that the two curves are very close and for this reason this equation was used in the mathematical model.

Specific Heat of Rice

The specific heat of rice was assumed to be represented by the equation

$$C = 0.0107\ M_{wb} + 0.265\ \frac{BTU}{lb\ rice\ °F}$$

but was converted to $\frac{BTU}{lb\ air\ °F}$ by the following series of steps.

(1) $C_1 = 0.0107\ M_{wb} + 0.265$

$W_m + W_d$ pounds of grain per layer lb/ft^2

(2) $C_2 = C_1\ (W_m + W_d) = (0.0107\ M_{wb} + 0.265)(W_m + W_d)$

From the definition of M_{wb}

(3) $M_{wb} = \frac{100\ W_m}{W_m + W_d}$

solving for $W_m + W_d$

$$W_m + W_d = \frac{100\ W_m}{M_{wb}}$$

substituting the derived expression for $W_m + W_d$ into equation (2)

$$C_2 = (0.265 + 0.0107\ M_{wb})\ \frac{100\ W_m}{M_{wb}}$$

As a consequence of equation (3)

$$W_d = \frac{(100 - M_{wb})\ W_m}{M_{wb}}$$

Rearranging the factors and substituting the expression for W_d we arrive at a new expression for C_2

$$C_2 = \frac{(0.265 + 0.0107\ M_{wb})\ W_d}{1 - 0.01\ M_w} \quad \frac{\text{BTU}}{°\text{F ft}^2}$$

From the definitions for Q' and γ

$Q' = \text{cfm}$

$\gamma = \text{specific weight of air } 0.075\ \text{lb/ft}^3$

Transforming the units

$$Q = Q' \times 60 \times \gamma$$

$$Q = Q' \times 4.5\ [\frac{\text{lb air}}{\text{hr-ft}^2}]$$

Finally dividing C_2 by Q and Δt the required specific heat unit conversion is complete

$$\frac{C_2}{Q\Delta t} = C = \frac{(0.265 + 0.0107\ M_{wb})\ W_d}{(1 - 0.01\ M_w)\ Q\Delta t} \quad [\frac{\text{BTU}}{\#\text{air } °\text{F}}]$$

$$R = \frac{W_d}{(1 - 0.01\ M_{wb})\ Q\Delta t}$$

$$C = (0.265 + 0.0107\ M_{wb})\ R\ [\frac{\text{BTU}}{\#\text{air } °\text{F}}]$$

Thin Layer Simulation

The drying process following the Thompson pattern was considered to be divided into separate processes (including temperature equilibration between the grain and air, moisture removal, and evaporative cooling of the air and the grain). These processes actually occur simultaneously but the process was divided up to simplify the simulation. The heat balances were written in terms of BTU per lb of dry air flowing through the layer.

Drying air temperature

The equilibrium temperature of the dry air and the rice was calculated by performing an adiabatic heat balance and was used as the drying temperature.

Drying air temperature as used here is the temperature of the air at the drying layer and should not be confused with the temperature of the heated air before it enters the drying column.

This heat balance is only an intermediate calculation to determine the drying air temperature and does not include moisture evaporation.

The equilibrium temperature of the rice and the air before drying was determined with the following heat balance.

$$0.24\ T_o + H_o\ (1060.8 + 0.45\ T_o) + C\ G_o =$$

$$0.24\ T_e + H_o\ (1060.8 + 0.45\ T_e) + C\ T_e$$

Where the subscript "o" refers to initial values and "e" to equilibrium values of air temperature T, grain temperature G, and absolute humidity H.

The first two terms on each side of the equation represent the initial and equilibrium heat content of the air and the third terms are the initial and equilibrium heat content of the rice. Solving this equation for the unknown equilibrium temperature

$$T_e = \frac{(0.24 + 0.45\ H_o)\ T_o + C\ G_o}{0.24 + 0.45\ H_o + C}$$

Moisture removed

The equilibrium moisture content M_e of the rice was calculated by determining the relative humidity of the air and using the equilibrium temperature from the above heat balances in the equilibrium moisture content equation.

$$M_e = \left[\frac{-\ln (1 - RH)}{1.39 \times 10^{-5}\ (T + 460)}\right]^{\frac{1}{1.91}}$$

Values for MR were then obtained using the above calculated M_e and values for M and M_o obtained experimentally.

These values of MR were placed into the equation (a) in order to obtain the values for the constants A and B.

These two constants are a function of the temperature; that is, the values of these coefficients change as the temperature is changed. To determine the nature of the relationship between the coefficients and the temperature, values of A(T) and B(T) were determined from Fig. 4 and Fig. 5 These values of the coefficient were plotted on rectilinear coordinates, but the values of B were well fitted to a straight line on semilog paper. Again linear and exponential relationships were obtained.

$$A(T) = C + DT$$

$$B(T) = a \exp (bT)$$

Using the least squares method the following values for the coefficients were obtained.

$C = -1.79810$

$D = 0.007484$

$a = 20.357$

$b = -0.0361$

Finally the equation for a thin layer was reached.

$$t = A \ln (MR) + B [\ln (MR)]^2$$

where

$A = -1.79810 + 0.007484\ T$

$B = 20.357 \exp (-0.0361\ T)$

A graphical comparison of the predicted and measured time profiles for the different temperatures is shown in Fig. 6.

Latent Heat of Water in Rice

The latent heat of water in rice was obtained by using the equation of Chung and Pfost.

$$\Delta H_{st} = R \left(\frac{T_1 T_2}{T_2 - T_1}\right) \ln \frac{P_2}{P_1}$$

where

$R = 1.98 \left(\frac{BTU}{lb\text{-}mol\ {}^\circ R}\right)$

$T = {}^\circ R$

The values for P_1 was obtained from the definition of relative humidity

$RH = \frac{P_1}{P_o} \times 100$, or $P_1 = \frac{RH}{100} \times P$: where P_o is the saturated vapor pressure of water at T_1 °R as found in the Keenan and Keys Steam tables (12); and where RH was obtained from the equilibrium moisture table of Wratten and Kendrick (18) at T. The values for P_2 was obtained in exactly the same manner using its associated temperature T_2: hence, ΔH_{st} can now be obtained.

Using values of ΔH_{st} obtained in the above manner the coefficient for rice in the Othmer equation

$$L = (1094 - 0.57 \text{ T °F}) (1.0 + a\, e^{-bM})$$

were then evaluated by the least square method resulting in

$$a = 1.67$$

$$b = 20.062$$

This equation was then proved by making a comparison between the values obtained from the Chung and Pfost equation for 94°F and the values obtained from the last equation. The values obtained from these two equations are very close (Table 1).

Final Air and Grain Temperature

The final air and grain state points consistent with the amount of drying performed on a thin layer of grain during time interval were calculated by the following method

$(\frac{M_o - M_f}{100})$ DM percent points of moisture were removed from the rice and evaporated into the air, thus the absolute humidity of the air was increased by an amount

$$\Delta H = \frac{(M_o - M_f) \text{ DM}}{100 \text{ QT}}$$

Table 1

Latent heat of water.

Comparison between the values obtained from the Chung and Pfost equation and Othmer equation with coefficients for rice at 94°F

ΔH_{ST} $(\frac{BTU}{lb})$	L $(\frac{BTU}{lb})$
1535.2241	1522.5491
1423.0571	1423.5800
1346.5885	1343.3970
1280.5532	1278.7433
1225.4267	1226.8602
1185.5979	1184.4094
1153.1242	1152.5661
1125.19037	1126.6121
1106.50451	1106.2260
1088.55663	1090.3199
1078.6346	1077.980
1067.8235	1068.4711

The final humidity is thus equal to the initial plus the incremental

$$H_f = H_o + \Delta H$$

The final temperature was determined with following heat balances

$$0.24\ T_e + H_o\ (1060.8 + 0.45\ T_e) + C\ G_o + \Delta H\ (G_o - 32)$$

$$0.24\ T_f + H_f\ (1060.8 + 0.45\ T_f) + C\ T_f + \Delta L \Delta H$$

The first two terms on each side of the equation are the initial and final heat content of the air; the third term is the initial and final heat content of the rice the fourth term on the left side of the equation is the heat content of the water that was evaporated and the last term in the equation is the heat of vaporization required to evaporate moisture from the rice above that required for the same amount of free water.

Solving for T_f

$$T_f = \frac{(0.24 + 0.45\ H_o)\ T_e - \Delta H\ (1060.8 + \Delta L + 32 - G_e) + C\ G_e}{0.24 + 0.45\ H_f + C}$$

where T_f is the final air and grain temperature.

The above description of the mathematical drying model presents the steps that were necessary to calculate the final air and grain condition after drying for a time interval Δt on a single layer of rice.

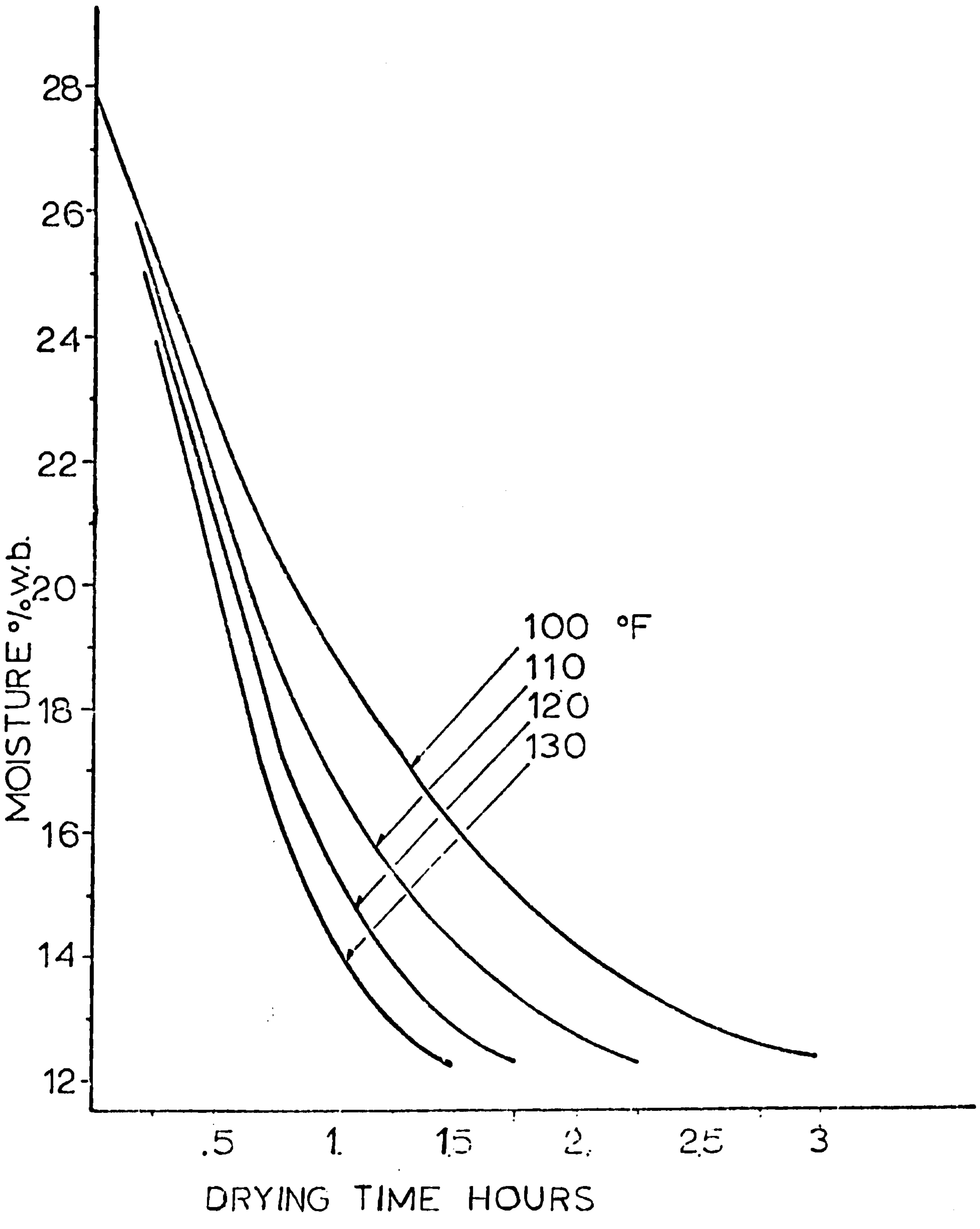

28
26
24
22
20
18
16
14
12
MOISTURE %.w.b.
.5
1.
1.5
2.
2.5
3
DRYING TIME HOURS
100 °F
110
120
130

FIG - 2

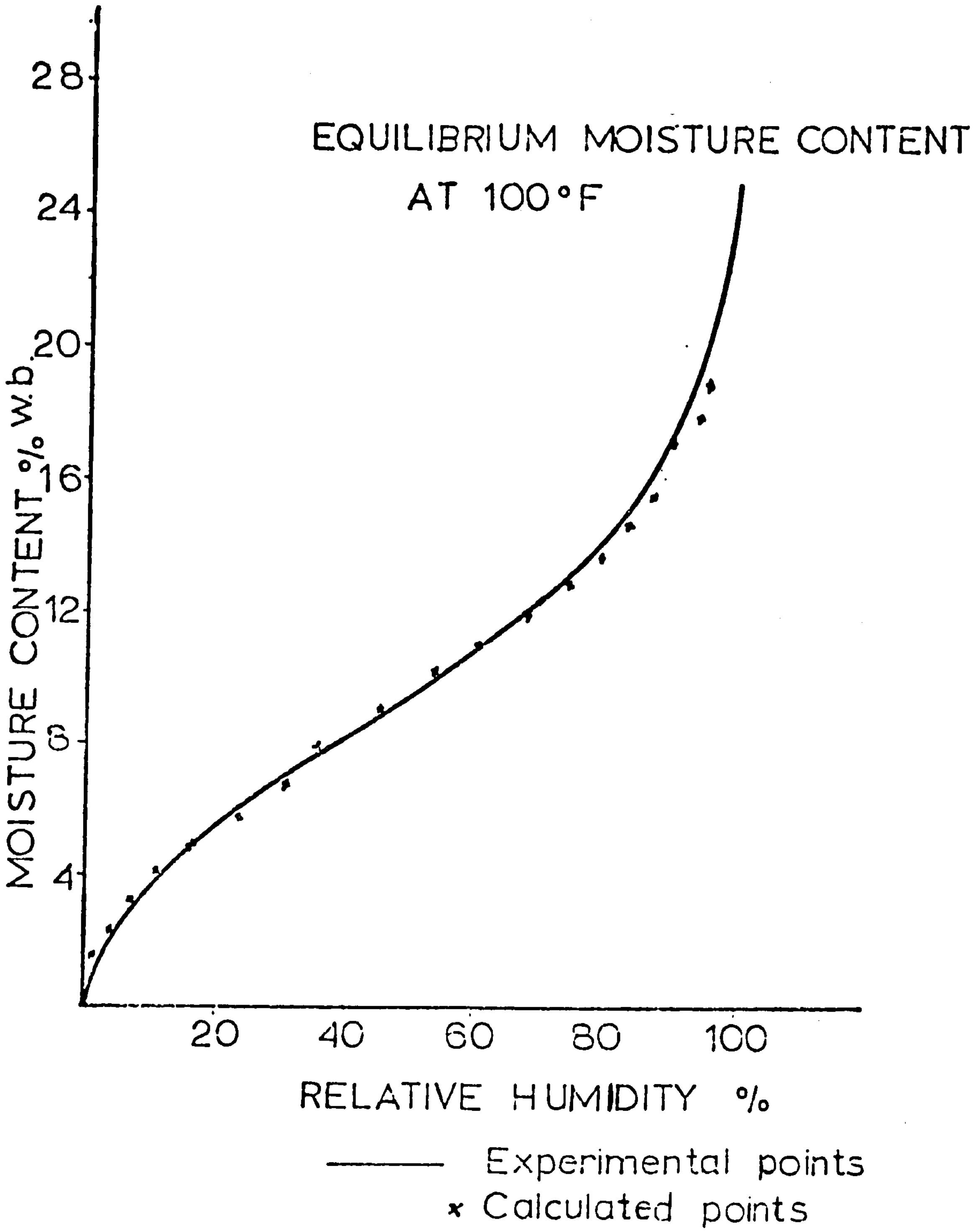

EQUILIBRIUM MOISTURE CONTENT
AT 100°F
MOISTURE CONTENT % w.b.
28
24
20
16
12
8
4
20
40
60
80
100
RELATIVE HUMIDITY %
——— Experimental points
× Calculated points

FIG-3

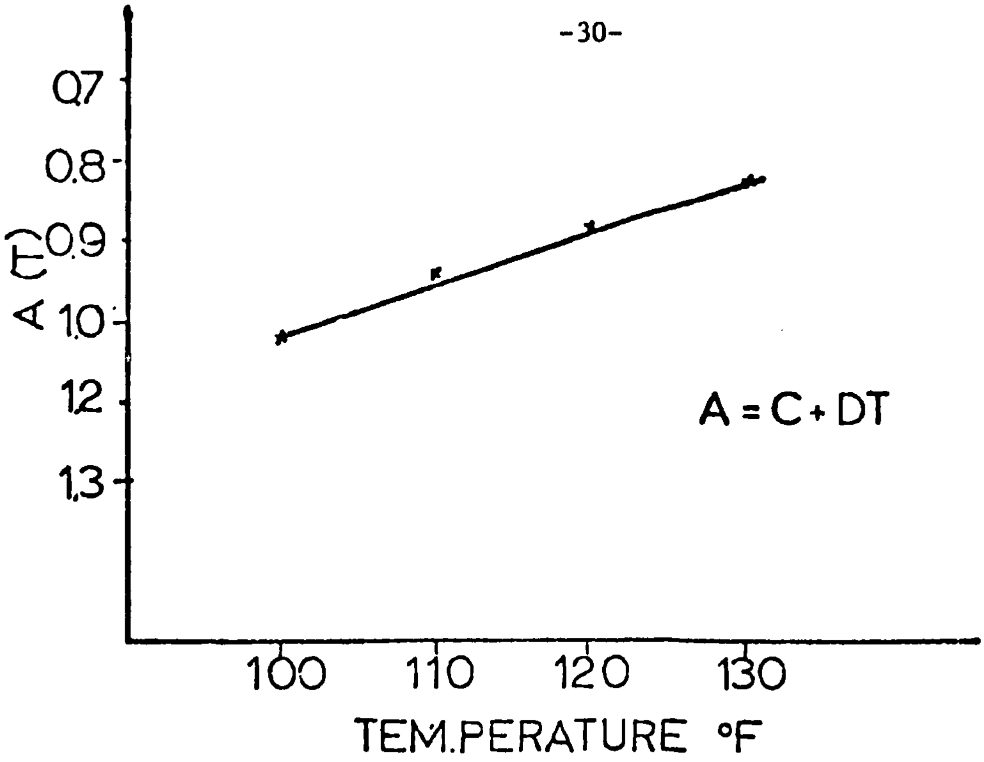
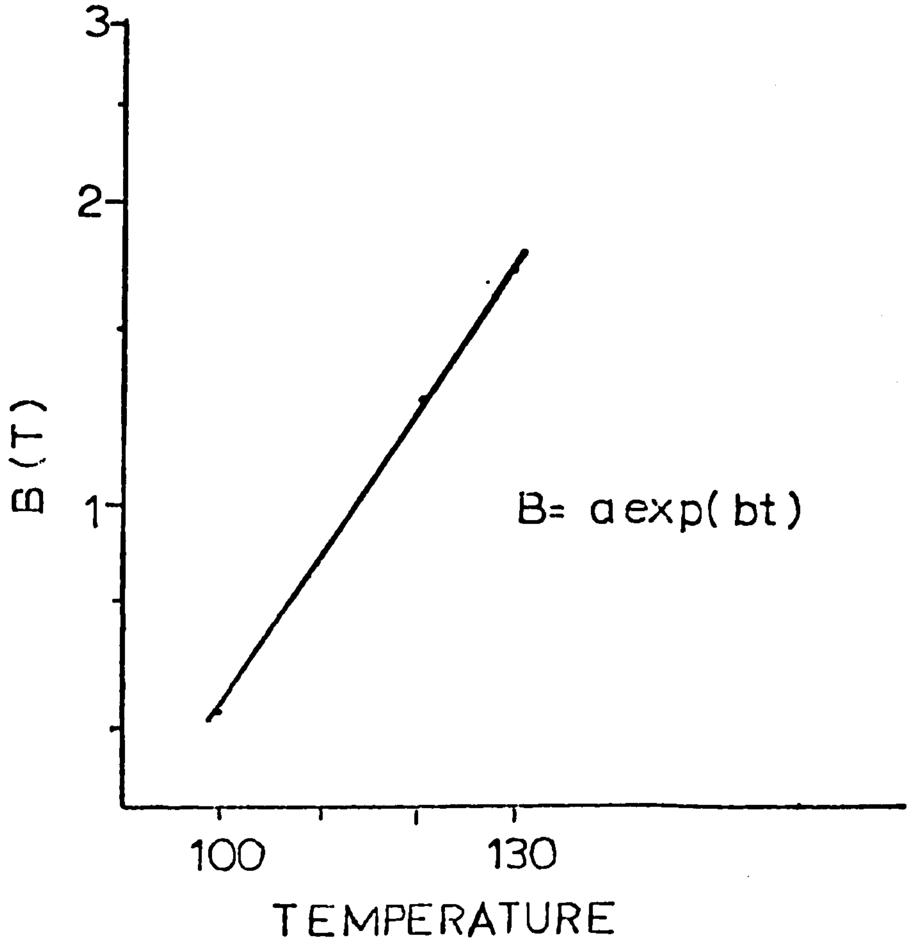

Q7
0.8
0.9
1.0
1.2
1.3
A (T)
A = C + DT
100
110
120
130
TEM.PERATURE °F

FIG 4 - 5


3
2
1
B (T)
B= a exp(bt)
100
130
TEMPERATURE

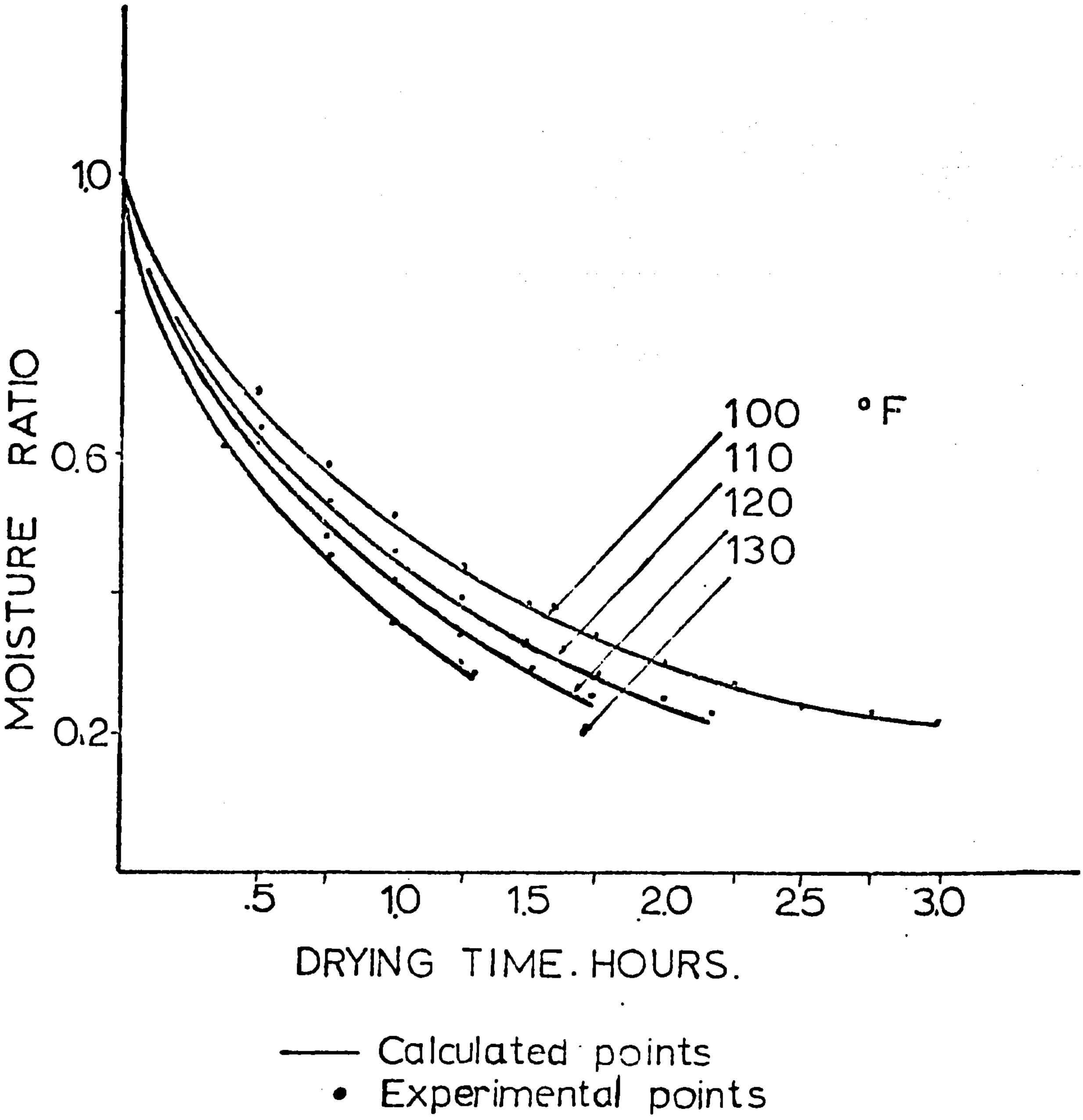

MOISTURE RATIO
1.0
0.6
0.2
.5
1.0
1.5
2.0
2.5
3.0
DRYING TIME. HOURS.
100 °F
110
120
130
—— Calculated points
• Experimental points

FIG - 6

FINAL AIR TEMPERATURE

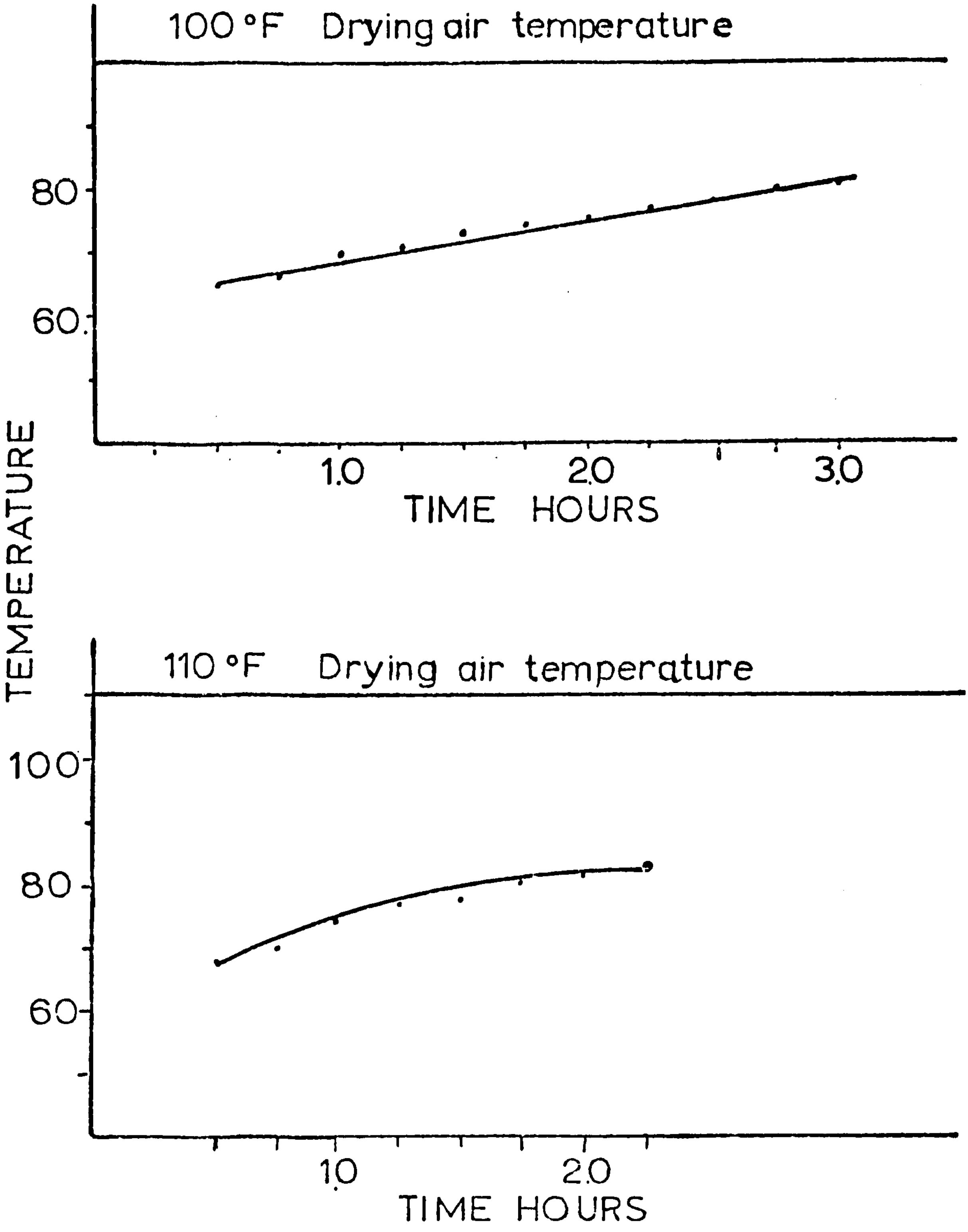


FIG - 7

FINAL AIR TEMPERATURE

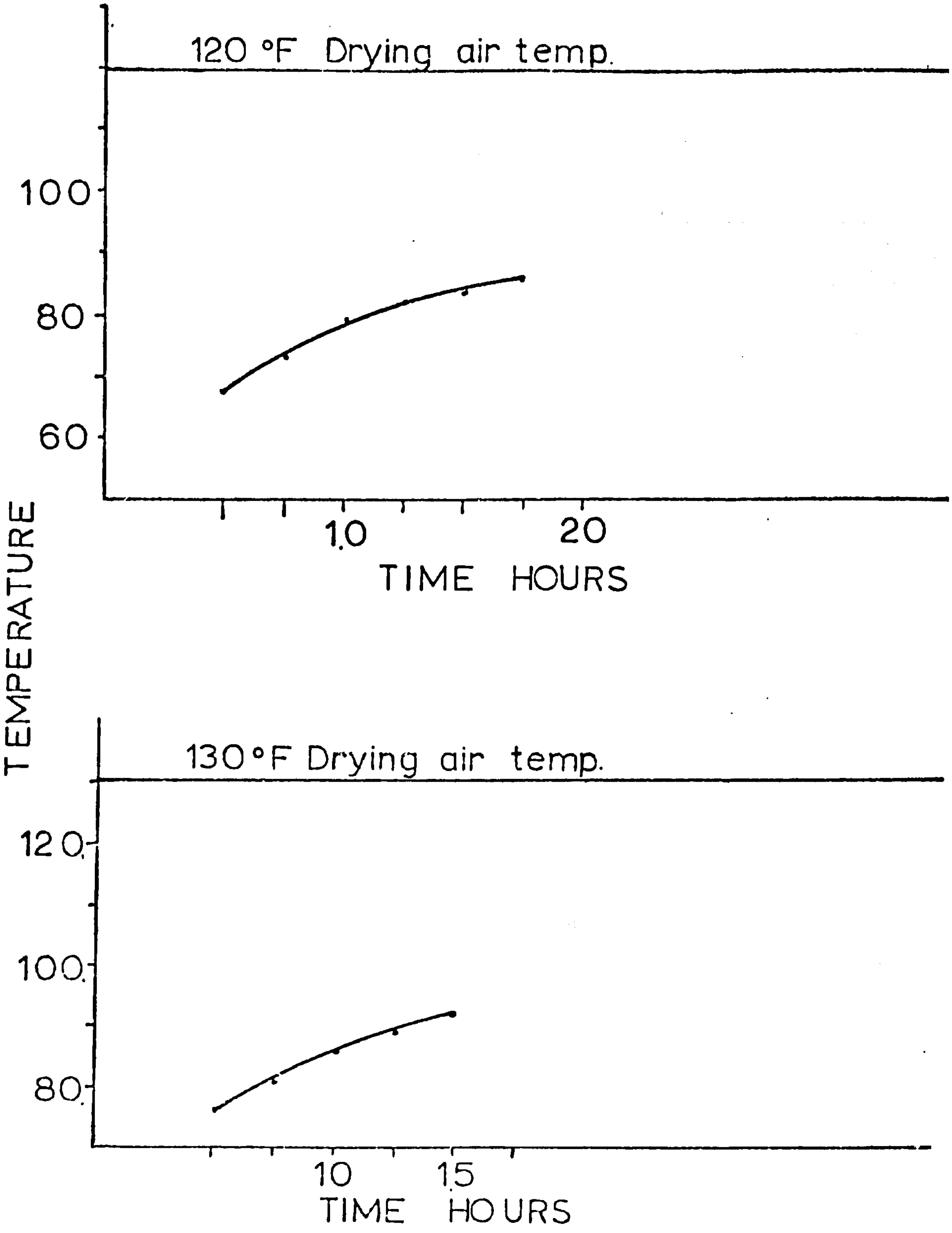


FIG-8

COMPARISON OF PREDICTED AND MEASURED RESULTS

A graphical comparison between the experimental drying results and those predicted by the equation

$$t = A \ln (MR) + B [\ln (MR)]^2$$

where $A = -1.7981 + 0.007484\ T$

$B = 20.357 \exp (-0.0361\ T)$

is made in Fig. 6 for 100°F, 110°F, 120°F and 130°F drying air temperatures. This graph shows a reasonable representation of the experimental results.

Table 2 shows values for equilibrium temperature and equilibrium moisture content. The values of equilibrium temperature were obtained from the equation

$$T_e = \frac{(0.24 + 0.45\ H_o)\ T_o + C\ G_o}{0.24 + 0.45\ H_o + C}$$

and the equilibrium moisture content was calculated by the Henderson formula.

In Table 3 are shown the final absolute temperature and the latent heat of water in rice. Values of latent heat were obtained from the equation

$$L = (1094 - 0.57\ T)\ (1 + ae^{bM})$$

at the end of each successive increment of time, for the different temperatures tested.

In Fig. 7 is shown the variation of final temperature of air versus drying time.

Table 2

Equilibrium moisture content and equilibrium temperature

Drying time decim	100°F			110°F		
	M % d.b.	T_e °F	M_e	M_o % d.b.	T_e °F	M_e
0.00	38.817			38.817		
0.50	29.215	94.576	7.27309	27.844	103.053	6.6953
0.75	25.738	96.261	7.26155	23.204	105.316	6.6813
1.00	23.485	97.160	7.2554	21.496	106.399	6.6746
1.25	20.98774	97.732	7.2515	19.193	107.128	6.6701
1.50	19.528	98.130	7.2488	16.665	107.640	6.6670
1.75	17.789	98.391	7.2470	15.740	107.976	6.6664
2.00	16.584	98.606	7.2455	14.442	108.284	6.6663
2.25	15.861	98.766	7.2444	13.960	108.443	6.6621
2.50	15.068	98.895	7.2436			
2.75	14.613	98.996	7.2429			
3.00	13.960	99.087	7.2423			

Drying time decim	120°F			130°F		
	M % d.b.	T_e °F	M_e	M_o % d.b.	T_e °F	M_e
0.00	38.8171			38.817		
0.50	26.608	111.587	6.196	25.004	120.149	5.592
0.75	21.384	114.366	6.180	19.899	123.331	5.576
1.00	19.573	115.671	6.173	16.365	125.036	5.568
1.25	16.900	116.566	6.168	14.616	126.044	5.563
1.50	14.904	117.170	6.164	13.921	126.697	5.559
1.75	13.921	117.579	6.162			
2.00						

Table 3

Final temperature and latent heat of water in rice at the end of each successive increment of time

Drying time decim	100°F		110°F		120°F		130°F	
	$L \frac{BTU}{lb}$	T_f °F	$L \frac{BTU}{lb}$	T_f °F	$L \frac{BTU}{lb}$	T_f °F	$L \frac{BTU}{lb}$	T_f °F
0.50	1045.038	65.97	1041.741	68.96	1038.666	68.985	1036.864	76.546
0.75	1049.058	66.94	1050.393	69.68	1052.356	73.592	1055.260	79.562
1.00	1054.210	70.01	1056.474	75.137	1061.900	80.206	1086.790	82.540
1.25	1064.020	71.114	1069.620	77.34	1085.370	82.167	1113.084	87.365
1.50	1072.536	73.65	1093.545	78.01	1113.472	84.136	1126.290	92.709
1.75	1086.769	74.37	1105.756	80.68	1132.019	86.946		
2.00	1100.008	75.79	1127.371	82.15				
2.25	1109.616	77.32	1136.937	84.34				
2.50	1121.936	78.55						
2.75	1129.938	80.125						
3.00	1142.811	80.720						

DISCUSSION OF DRYING RESULTS

It was observed in the different tests that the drying rate was faster at the beginning of the drying operation, when the surfaces of the kernels were moist, than it was after the surface moisture had been reduced.

The equation for thin layer drying was used to calculate the time that it took grain of 26%, 24% and 22% initial moisture content to reach the 12.5% final moisture content using 100°F, 110°F, 120°F and 130°F drying air temperatures. As might be expected the grain that was higher in initial moisture took more time to reach this final value for each temperature.

Grain at 26% initial moisture content that was dried at 120° or 130°F reached the final moisture content in a shorter time than grain that was at 22% but was dried at 100°F. For this reason we can say that the temperature of the drying air was the principal factor in the rate of drying.

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